

# COMPARISON OF VAPOR-PRESSURE-DEFICIT CALCULATION METHODS—SOUTHERN HIGH PLAINS

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**ABSTRACT:** Vapor-pressure deficit (*VPD*) affects evapotranspiration, water-use efficiency, and radiation-use efficiency of crops. *VPD* calculation methods were evaluated for a semiarid environment in the Southern Great Plains. Air temperature and relative humidity were measured near Bushland, Texas, during 1992 and 1993. Temperature and relative humidity were measured at 0.17 Hz (6 s), averages were recorded for each 15-min period, and daily (24-hr) maximums, minimums, and averages were recorded. *VPD*, actual vapor pressure, and dew-point temperatures were computed and averaged for each 15-min period and day. Methods that used mean daily dew-point temperature to compute daily actual vapor pressure performed well, and methods that used hybrid calculations based on maximum and minimum air temperature and relative humidity performed the worst. Methods using one-time-of-day dew-point temperatures as recommended by the 1990 ASCE *Manual No. 70* should be used with caution in this environment. Weather data sets containing maximum and minimum temperatures and daily mean dew-point temperature should provide the most accurate calculations of *VPD* in this environment.

## INTRODUCTION

Vapor-pressure deficit (*VPD*) is an important parameter that is computed in evapotranspiration (ET) models, particularly combination-type equations and Penman-Monteith-type formulas, and for crop models, because *VPD* affects crop growth. A wide diversity of data and methods for computing *VPD* are used. Reviews of the methods employed to compute *VPD* are found in Jensen et al. (1990), and a thorough analysis is given by Sadler and Evans (1989) on the effects of *VPD* methods on computed ET across much of the United States. *VPD* estimation methods need to make use of readily available weather data and need to be verified in particular environments where possible. Sadler and Evans (1989) demonstrated that 15 different *VPD* calculation methods could cause ET errors from 80% underestimation to 100% overestimation compared to their best *VPD* method for a Van Bavel (1966) type combination ET equation across a wide range of environments. The routine collection of weather data with remote automated weather stations (Howell et al. 1984) also requires information on *VPD* measurement and data processing to minimize potential distortion in the climatic record.

The most troublesome problem with methods for estimating *VPD* is the systematic biases that affect computed ET and can occur with a particular *VPD* method. In addition, atmospheric humidity data are often measured and reported in inconsistent formats. Small differences in calculation methods can have subtle and important effects on computed ET (Sadler and Evans 1989). Also, exact methods for measuring, recording, computing, and estimating atmospheric humidity are often not reported. In advective environments, like the Great Plains, the atmospheric term of the combination equation (Penman 1948) can dominate the radiative term (Rosenberg and Verma 1978; Howell et al. 1993), in some situations leading to ET rates for "well-watered" crops in excess of 220% of equilibrium ET (McIlroy and Angus 1964; Priestley and Taylor 1972) based mainly on net radiation. Equally troublesome is the fact that empirical wind functions derived for combination ET equations are applicable for only a narrow range of *VPD* calculation methods (Jensen 1974; Doorenbos and Pruitt 1977; Cuenca and Nicholson 1982; Burman et al. 1983; Heermann 1985; Jensen et al. 1990). The interaction of diurnal wind speeds and *VPD* is known to affect the performance of combination equations (Doorenbos and Pruitt 1977), and in many cases correction factors need to be used to adjust for these errors (Jensen et al. 1990).

Tanner and Sinclair (1983) indicated that *VPD*, and more importantly daytime *VPD*, was a dominant factor influencing the relation between crop dry-matter production and water use. *VPD* has also been shown to affect the radiation-use efficiency of crops (Stockle and Kiniry 1990; Manrique et al. 1991; Kiniry et al. 1992).

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The purpose of this paper is to present an analysis of *VPD* estimation methods for conditions common to the Southern High Plains of the United States. In particular, the *VPD* methods used in the *ASCE Manual No. 70* (Jensen et al. 1990) will be analyzed for their applicability to this environment, and appropriate methods for this region will be recommended.

## PROCEDURES

Air temperature and relative humidity were measured in 1992 and 1993 at the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) Conservation and Production Research Laboratory at Bushland, Texas [lat. 35°11' N; long. 102°06' W; 1,170 m above mean sea level (MSL)] [see Dusek et al. (1987) for site layout details]. The weather station is 1,520 m<sup>2</sup> in area, has an irrigated grass (cool-season lawn mixture containing bluegrass, perennial ryegrass, etc.) sod that is regularly mowed and maintained (flood irrigated and fertilized), and surrounded by agricultural fields. Air-temperature and relative-humidity data were measured using a Rotronic MP100 sensor (Rotronic, Inc., Huntington, N.Y.) mounted in a "cotton belt" instrument shelter at about 1.5 m above the ground. The sensor was excited and measured every 6 s (0.17 Hz) with a CR-7X data logger (Campbell Scientific, Inc., Logan, Utah). Data were translated into engineering units of °C for temperature and percentage (%) for relative humidity by the data-logger program and processed by the data logger into 15-min time period (150 samples) averages ( $T_i$  and  $RH_i$ , where each represents 15-min periods), daily (24 hr) averages ( $T_{avg}$  and  $RH_{avg}$ ), and daily maximum and minimum sample values for each parameter ( $T_{max}$ ,  $T_{min}$ ,  $RH_{max}$ , and  $RH_{min}$ ). Data were transferred daily via telecommunications to a personal computer (PC). Dew-point temperatures ( $T_{dew}$ ) and ambient vapor pressure ( $e_a$ ) were computed for each time period using the following equations from Murray (1967):

$$T_{dew(i)} = \frac{237.3}{\left[ \frac{1}{\left[ \frac{\ln \left( \frac{RH_i}{100} \right)}{17.27} \right] + \left[ \frac{T_i}{(237.3 + T_i)} \right]} - 1 \right]} \quad (1)$$

$$e^*(T_i) = 0.611 \exp \left[ \frac{17.27 T_i}{(T_i + 237.3)} \right] \quad (2)$$

where  $T_{dew(i)}$  = dew-point temperature in °C;  $T_i$  = air temperature in °C;  $RH_i$  = air relative humidity in %; and  $e^*(T_i)$  = saturated vapor pressure in kPa for temperature  $T_i$  in °C for the  $i$ th period of each day.

The parameter  $T_{dew,08}$  was computed as the 30-min mean dew-point temperature from 8:00 to 8:30 a.m. central standard time (CST) at Bushland using the two 15-min mean  $T_i$  and  $RH_i$  values for 8:15 and 8:30 a.m. representing the 8:00–8:30 average. Also,  $T_{dew,08}$  was intended to simulate a one-time-of-day dew-point observation at 8:00 central daylight time (CDT) like that used by Wright (1982) and Jensen et al. (1990).

A few days (25 days in all) of data were omitted from the record due to various problems (data logger, instrument performance, quality control, etc.), and the complete record contained data for 706 days. The Rotronic MP100 sensor signal was compared to other temperature/relative-humidity instruments including a ventilated, wet-dry bulb psychrometer patterned after Lourence and Pruitt (1969) (the psychrometer was only operational during nonfreezing conditions). The coefficient of determination comparing the Rotronic air temperature in the shelter to the shielded, aspirated psychrometer exceeded 0.999 for over 1,000 hours of consecutive operation, and the coefficient of determination comparing the Rotronic relative humidity to that computed from the wet- and dry-bulb temperatures exceeded 0.996 for the same period. Readers are referred to Dusek et al. (1993) for further details regarding instrument performance and other instrumentation for temperature/relative-humidity measurements.

Daily mean *VPD* in kPa was computed as follows:

$$VPD = \frac{\sum_{i=1}^{96} \left[ e^*(T_i) \left( 1 - \frac{RH_i}{100} \right) \right]}{96} \quad (3)$$

where  $T_i$  and  $RH_i$  = 15-min mean values for air temperature and relative humidity. Daytime *VPD* ( $VPD_{dt}$ ) was computed as an average of the 15-min *VPD* values from 7:00 a.m. to 7:00 p.m. CST (48 values in the average) at Bushland representing the average daylight hours. The 24-hr (daily) mean vapor pressure ( $e_a$ ) was computed as follows:

$$e_d = \frac{\sum_{i=1}^{96} \left[ e^*(T_i) \left( \frac{RH_i}{100} \right) \right]}{96} \quad (4)$$

### Vapor-Pressure Deficit Calculation Methods

The *VPD* methods used are listed in Table 1. Methods 1–4 correspond to the definitions found in Jensen et al. (1990; p. 97). In these methods, mean daily air temperature ( $T_{\text{mean}}$ ) was determined as the simple average of the daily maximum ( $T_{\text{max}}$ ) and minimum ( $T_{\text{min}}$ ) air temperatures, and some methods (mainly 1A and 2A) used whole day (24 hr) average air temperatures or relative humidities ( $T_{\text{avg}}$  and  $RH_{\text{avg}}$ , respectively). Method 5 used the hybrid calculations with maximum and minimum  $RH$  and  $T$ . These were compared with values from (3) that would be similar to “Method 5” listed in Jensen et al. (1990) and to “Method 13” in Sadler and Evans (1989) that would be considered to be a valid standard. Method 1 is basically the *VPD* method used by Penman (1948) and many others, including Steiner et al. (1991), for some of our earlier ET research at Bushland; Doorenbos and Pruitt (1977) mainly recommended methods 1 and 2. Method 3 is used by Howell et al. (1993) and is currently being used by ARS at Bushland. Method 3A is the recommended method by Jensen et al. (1990), as used by Wright (1982), Allen (1986), and Allen et al. (1989); however, Sadler and Evans (1989) mentioned their concerns about one-time-of-day dew-point temperatures used in method 3A. Method 5 is being used in the South Plains potential evapotranspiration (PET) network (Lascano and Salisbury 1993) at Lubbock, Texas, in the Southern High Plains. Sadler and Evans (1989) evaluated a more thorough list of *VPD* methods, but these certainly represent nine widely used methods. In addition, evaluations were performed to determine optimum methods for estimating daily mean saturated vapor pressure ( $e_a$ ) and mean daily vapor pressure ( $e_d$ ), and are listed in Table 2 and Table 3, respectively.

The purpose of this evaluation was to validate our *VPD* calculation methods (methods 1 and 3) and to see how our methods compared to others. This study was not intended to be an exhaustive comparison of every available *VPD* calculation method. These methods all use readily available data such as  $T_{\text{max}}$ ,  $T_{\text{min}}$ ,  $RH_{\text{max}}$ , and  $RH_{\text{min}}$ , but admittedly data for parameters such as  $T_{\text{dew}}$  and  $T_{\text{dew}08}$  may not be that readily available. However, hourly data for  $T$  and  $RH$  are becoming more widely available from automated weather stations across the United States. The resulting parameters were analyzed using linear-regression and statistical-analysis methods using STATGRAPHICS (v.5.0) (STSC, Inc., Rockville, Md.).

### RESULTS AND ANALYSIS

The weather-station fetch is limited to approximately 20–25 m in most cases. Hielman et al. (1989) demonstrated that air-temperature and relative-humidity profiles measured by Bowen ratio over irrigated grass with a low aerodynamic roughness were stable at fetch-to-height ratios as low as 20:1 and only slightly reduced evaporation fluxes at fetch-to-height ratios as low as 14:1. The limited fetch is not believed to be a serious problem. The open, unobstructed fetch during noncropping periods exceeded several hundred meters of bare soil, residue-covered soil, or low-growing irrigated crops. Brutsaert (1982) provides additional discussion on the limitations of fetch, but reported variations can be found in the literature for the necessary fetch-to-height ratio from 10:1 to over 200:1 for profile equilibrium with the surface conditions.

The effect of solar heating of the cotton-belt shelter should be minimal due to the normally strong, prevailing winds. The good correspondence between the air temperatures measured in the shelter to those measured by the shielded, aspirated psychrometer (Dusek et al. 1993) substantiates this hypothesis.

### Vapor-Pressure Deficit Calculations

Regression results between daily *VPDs* computed as the daily average of the 15-min values and the various *VPD* calculation methods are given in Table 1. Regression results for methods 1, 3, and 3A are shown in Fig. 1. All regressions were highly significant ( $P < 0.05$ ), and coefficients of determination ranged from 0.701 for method 5 to 0.996 for methods 1 and 2A. Methods 2A and 3 had nonsignificant ( $P < 0.05$ ) intercepts, and those regressions were forced through the origin. Intercepts for the other methods were small (less than  $\pm 0.103$  kPa), except for method 1A and 4, which had respective intercepts of 0.230 and 0.336 kPa. The average daily *VPD* was 0.813 kPa, and the standard errors of the estimate ( $S_{yx}$ ) for the regressions ranged from 36.4% of this mean for method 5 to only 4.4% for method 1. *VPD* calculation methods and the data used to compute *VPD* affected the performance of the predicted *VPD*. If an arbitrary criterion of 25% error was established on *VPD*, only methods 4 and 5 would not be recommended. If the error criterion was increased to 15% error in *VPD*, only methods 1, 2, and 2A would be recommended. We recommend that methods 4 and 5 not be used in an

**TABLE 1. Regression Results between Nine Methods (Dependent Variable) for Estimating Daily VPD Compared with Diurnal Average VPD (Independent Variable)**

Description (1)	Dependent variable (VPD) (2)	Intercept (kPa) (3)	Slope (dimensionless) (4)	$r^2$ (dimensionless) (5)	$S_{y,x}$ (kPa) (6)
Method 1	$[e^*(T_{mean})] - [e^*(T_{dew})]$	-0.013	0.910	0.996	0.036
Method 1A	$[e^*(T_{avg})] - [e^*(T_{dew})]$	0.230	1.065	0.907	0.200
Method 2	$[e^*(T_{mean})][1 - (RH_{mean}/100)]$	0.059	0.782	0.965	0.087
Method 2A	$[e^*(T_{avg})][1 - (RH_{avg}/100)]$	— <sup>a</sup>	0.827	0.996	0.056
Method 3	$\{[e^*(T_{max}) + e^*(T_{min})]/2\} - e^*(T_{dew})$	— <sup>a</sup>	0.959	0.983	0.125
Method 3A	$\{[e^*(T_{max}) + e^*(T_{min})]/2\} - e^*(T_{dew}08)$	0.091	0.826	0.885	0.174
Method 4	$\{[e^*(T_{max}) - e_d] + [e^*(T_{min}) - e^*(T_{dew})]/2\}$	0.336	1.250	0.906	0.237
Method 5	$\{[e^*(T_{max}) + e^*(T_{min})]/2\} - \{[e^*(T_{min})](RH_{max}/100) + [e^*(T_{max})](RH_{min}/100)/2\}$	-0.213	0.770	0.701	0.296

Note: Data from 15-min means throughout the day for 1992 and 1993 at Bushland, Texas ( $N = 706$ ).

<sup>a</sup>Not significant.

**TABLE 2. Regression Results between Two Methods (Dependent Variable) for Estimating Daily Mean Saturated Vapor Pressure ( $e_s$ ) Compared with  $e_s$  Estimated Using  $T_{max}$  and  $T_{min}$  Daily Values**

Description (1)	Dependent variable ( $e_s$ ) (2)	Intercept (kPa) (3)	Slope (dimensionless) (4)	$r^2$ (dimensionless) (5)	$S_{y,x}$ (kPa) (6)
Method 1	$e^*(T_{mean})$	-0.035	0.990	0.972	0.153
Method 1A	$e^*(T_{avg})$	-0.033	1.038	0.983	0.123

Note: Data from 6-s samples of  $T$  throughout the day for 1992 and 1993 at Bushland, Texas ( $N = 706$ ).

**TABLE 3. Regression Results between Five Methods (Dependent Variable) for Estimating Daily Mean Vapor Pressure ( $e_a$ ) Compared with Diurnal Average  $e_a$  Computed from 15-min Means of Air Temperature ( $T$ ) and Relative Humidity ( $RH$ ) Throughout Day**

Description (1)	Dependent variable ( $e_a$ ) (2)	Intercept (kPa) (3)	Slope (dimensionless) (4)	$r^2$ (dimensionless) (5)	$S_{y,x}$ (kPa) (6)
Method 1	$e^*(T_{dew})$	-0.001	0.990	0.999	0.002
Method 2	$e^*(T_{dew}08)$	-0.030	1.040	0.941	0.141
Method 3	$\{[e^*(T_{min})](RH_{max}/100) + [e^*(T_{max})](RH_{min}/100)/2\}$	-0.026	1.400	0.983	0.100
Method 4	$[e^*(T_{mean})](RH_{mean}/100)$	0.044	1.010	0.971	0.094
Method 4A	$[e^*(T_{avg})](RH_{avg}/100)$	0.019	1.029	0.992	0.051

Note: Data for 1992 and 1993 at Bushland, Texas ( $N = 706$ ).

environment like the Southern High Plains and that method 3A be used with caution [as noted earlier by Sadler and Evans (1989)]. Method 3, currently used by ARS at Bushland, is within  $\pm 16\%$  of actual mean daily VPD, on the average; has a slope near 1.0 (actually 0.959); has no significant bias (offset); and has a high correlation coefficient ( $r = 0.992$ ) to actual VPD.

## Estimating VPD Parameters

Regression results for two methods for estimating mean  $e_a$  were compared with the ASCE Manual No. 70 (Jensen et al. 1990) recommended method and are shown in Table 2 and Fig. 2. The mean  $e_a$  value was 1.729 kPa, and both methods were acceptable with errors less than 9% of the mean, slopes near 1.0, and a small offset bias (intercept). Regression results for five methods for estimating  $e_a$  were compared with values computed with (4) and are shown in Table 3. The regression results for methods 2–4 are shown in Fig. 3. The mean daily  $e_a$  was 0.958 kPa, and all the methods had errors less than 15% of the mean value, high linearity ( $r^2$  near 1.0), and small offset bias (small intercept). But method 3, using the hybrid  $T$  and  $RH$  data, overpredicted daily mean  $e_a$  at this location. Method 2 using the recommended one-time-of-day dew-point temperature had the largest error in predicting  $e_a$ , but its slope was near 1.0 and it had a small offset bias. The results for method 1 simply reflect the manner in which the data were computed, and are self-correlation for the most part.

We recommend that routine weather data for ET calculations include  $T_{max}$ ,  $T_{min}$ , and  $T_{dew}$  to simplify and standardize records, and  $T_{avg}$  could be included if space was available. These

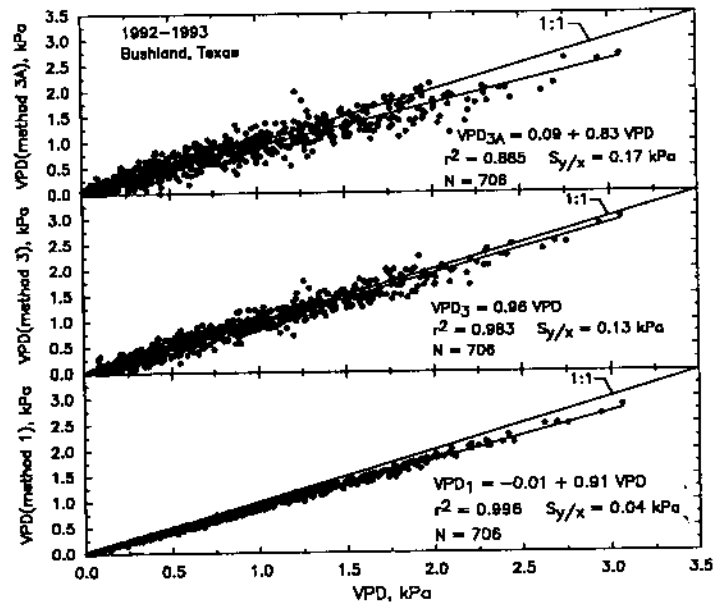


FIG. 1. Regression Relationships for Three Daily VPD Calculation Methods Compared to Mean Daily VPD

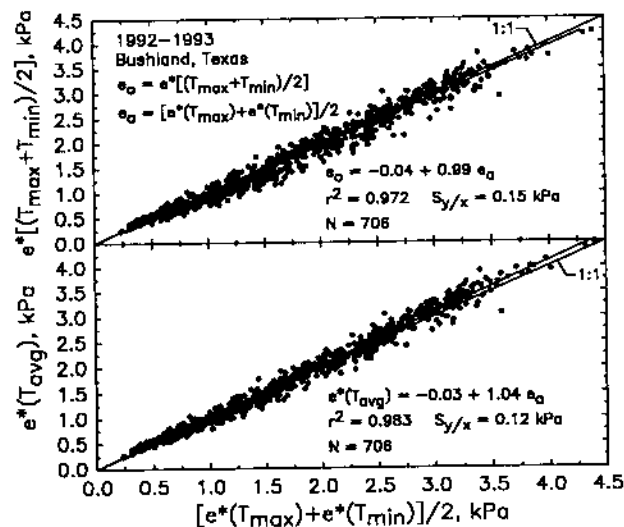


FIG. 2. Regression Relationships for Two Daily Saturated-Vapor-Pressure Calculations Compared to ASCE Manual No. 70 Method

three or four parameters are the optimum set for estimating daily  $VPD$  in this type of semiarid environment. The rather good relationships found between measured  $VPD$  and estimated  $VPD$  using  $T_{avg}$  and  $RH_{avg}$  (method 2A) and even using  $T_{min}$  and  $RH_{min}$  (method 2) were somewhat unexpected because of the nonlinearity of the  $e^*(T)$  function with  $T$ . These two methods need to be validated at other locations to test their suitability. Of course, mean daily  $T_{dew}$  data require hourly (or more frequently) outputs of averaged  $T$  and  $RH$  data measured at least as frequently as 16.7 mHz (once every minute).

### Estimating Environmental Parameters

Daytime  $VPD(VPD_{dt})$  was strongly correlated to daily mean  $VPD$  as shown in Fig. 4. The mean  $VPD_{dt}$  was 1.24 kPa. The resulting regression equation was  $VPD_{dt} = 1.52VPD$  with  $r^2 = 0.996$  and  $S_{y/x} = 0.099$  kPa. The daytime  $VPD$  at Bushland can be estimated rather conservatively as 150% of daily mean  $VPD$  for most cases. This relationship can be used with water use efficiency ratios from Tanner and Sinclair (1983) and Howell (1990), and with crop models (Kiniry et al. 1992) to improve their performance in this environment.

Table 4 gives the regression results for relationships that may be of interest and use for estimating surrogate  $VPD$  parameters. The minimum temperature ( $T_{min}$ ) could be a surrogate variable for dew point temperature ( $T_{dew}$ ) although it could not be used directly at this semiarid

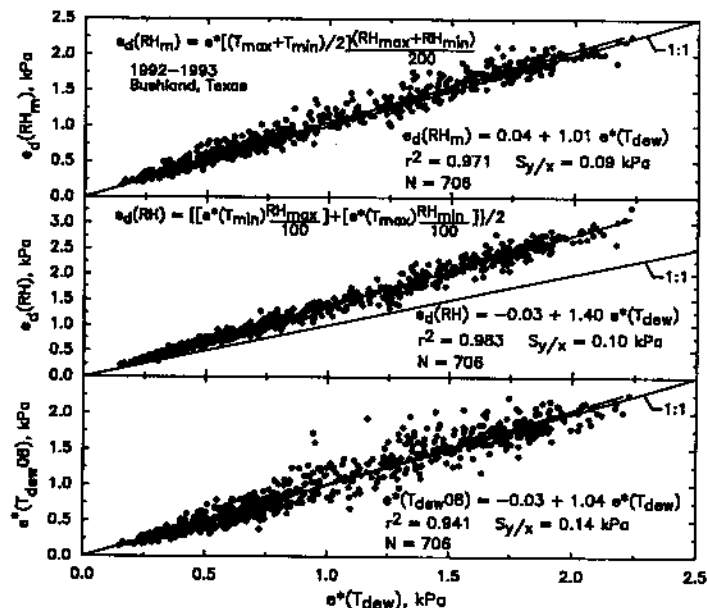


FIG. 3. Regression Relationships for Three Mean Daily Vapor-Pressure Calculations Compared to Mean Daily Vapor Pressure

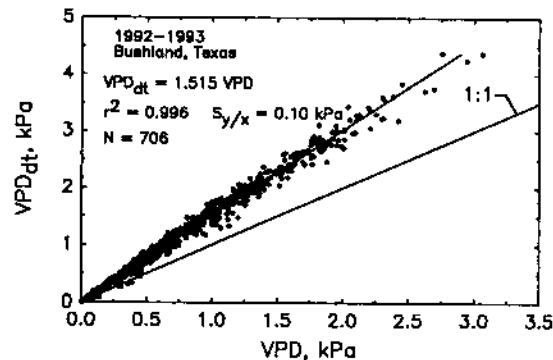


FIG. 4. Regression Relationship for Daytime VPD ( $VPD_{dt}$ ) Compared to Mean Daily VPD

TABLE 4. Regression Results between Several Humidity and Temperature Parameters

Dependent		Independent		Intercept (5)	Slope (6)	$r^2$ (7)	$S_{y/x}$ (8)
Variables (1)	Units (2)	Variables (3)	Units (4)				
$RH_{avg}$	%RH	$(RH_{max} + RH_{min})/2$	%RH	-5.76	1.13	0.934	4.14
$T_{dew08}$	°C	$T_{dew}$	°C	— <sup>a</sup>	1.05	0.952	2.22
$T_{dew08}$	°C	$T_{dew}$	°C	1.34	1.00	0.899	2.96
$T_{dew}$	°C	$T_{min}$	°C	-0.92	0.90	0.856	3.27
$T_{avg}$	°C	$(T_{max} + T_{min})/2$	°C	-0.53	1.00	0.991	0.88

Note: Data for 1992 and 1993 at Bushland, Texas ( $N = 706$ ).

<sup>a</sup>Not significant.

location as suggested by Merva and Fernandez (1985) for humid sites. The  $T_{mean} [(T_{max} + T_{min})/2]$  was similar to  $T_{avg}$  computed from all the daily  $T$  measurements, and  $RH_{mean} [(RH_{max} + RH_{min})/2]$  was also similar to  $RH_{avg}$  computed from all the daily  $RH$  measurements.

## SUMMARY AND CONCLUSIONS

VPD estimation methods for use in the Southern High Plains need to be carefully evaluated. Most of the methods outlined in the ASCE Manual No. 70 (Jensen et al. 1990) would be acceptable (errors less than 20–25%). The ASCE Manual No. 70 recommended method (method 3A here) using the one-time-of-day dew-point temperature did not provide as good daily VPD values as other methods in this environment. Both of the VPD methods used by ARS at Bushland [method 1 used by Steiner et al. (1991) and method 3 used by Howell et al. (1994)] provided acceptable agreement with actual mean daily VPD. The estimation of daily mean VPD from

daily climatic parameters ( $T_{\max}$ ,  $T_{\min}$ ,  $RH_{\max}$ ,  $RH_{\min}$ , and  $T_{\text{dew}}$  or  $T_{\text{dew}08}$ ) remains empirical. But the methods evaluated here are being used in various forms in many evapotranspiration models and often without adequate testing. The  $VPD$  calculation method introduces a bias error rather than a systematic random error, which has much less serious consequences. Particularly, the hybrid  $VPD$  computation method using maximum and minimum values of daily air temperature and relative humidity (method 5) can lead to a serious underprediction of  $VPD$  in this environment. Likewise, the average of  $VPDs$  at  $T_{\max}$  and  $T_{\min}$  (method 4) can lead to serious overprediction of  $VPD$  in this environment.

Daytime  $VPD$  is about 1.5 times mean 24-hr (daily)  $VPD$  at Bushland, and this relationship can improve estimates of water use efficiency and crop-growth modeling. Minimum daily air temperature ( $T_{\min}$ ) could be used for an approximation to mean daily dew-point temperature in this semiarid environment if it was adjusted with a regression equation like the one given here. Weather data sets are recommended to include  $T_{\max}$ ,  $T_{\min}$ , and  $T_{\text{dew}}$  to simplify and standardize the records, and to include  $T_{\text{avg}}$  if space is available.

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## APPENDIX II. NOTATION

The following symbols are used in this paper:

- $e_a$  = 24-hr saturated vapor pressure  $\{[e^*(T_{\max}) + e^*(T_{\min})]/2\}$ , kPa;
- $e_d$  = 24-hr mean vapor pressure computed from 15-min means of air temperature and relative humidity, kPa;
- $e^*(T)$  = saturated vapor pressure at temperature,  $T$ , kPa;
- $N$  = number of samples;
- $r^2$  = coefficient of determination;
- $RH_{\text{avg}}$  = 24-hr mean air relative humidity (of 14,400 6-s samples every day), %;
- $RH_i$  = air relative humidity (usually defined as mean value of 600 6-s samples for each 15-min time period), %;
- $RH_{\max}$  = maximum air relative humidity (of 14,400 6-s samples every day) throughout day, %;
- $RH_{\text{mean}}$  =  $(RH_{\max} + RH_{\min})/2$ , %;
- $RH_{\min}$  = minimum air relative humidity (of 14,400 6-s samples every day) throughout day, %;
- $S_{y/x}$  = standard error of estimate;
- $T_i$  = air temperature (usually defined as mean value of 600 6-s samples for each 15-min time period), °C;
- $T_{\text{avg}}$  = 24-hr mean air temperature (of 14,400 6-s samples every day), °C;
- $T_{\text{dew}}$  = computed dew point temperature for every 15-min period or mean of 96 15-min values for day, °C;
- $T_{\text{dew}08}$  = mean dew-point temperature for half hour from 8:00 to 8:30 a.m. CST (computed from 15-min mean  $T_i$  and  $RH_i$  values at 8:15 and 8:30 a.m. CST) at Bushland, Texas, °C;
- $T_{\max}$  = maximum air temperature (of 14,400 6-s samples every day) throughout day, °C;
- $T_{\text{mean}}$  =  $(T_{\max} + T_{\min})/2$ , °C;
- $T_{\min}$  = minimum air temperature (of 14,400 6-s samples every day) throughout day, °C;
- $VPD$  = vapor-pressure deficit (defined as mean value for day, 24-hr, computed from 15-min means of air temperature and relative humidity), kPa; and
- $VPD_{dt}$  = mean daytime (defined as 7:00 a.m. to 7:00 p.m. CST at Bushland, Texas) vapor-pressure deficit, kPa.